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Peculiar Galaxies

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Peculiar Galaxies

A peculiar galaxy is an object that cannot be easily classified as a SPIRAL, ELLIPTICAL, or IRREGULAR GALAXY based on its optical morphology. They constitute between 5% and 10% of the known galaxy population, although most 'normal' galaxies will show peculiar features if examined carefully. Peculiar galaxies show a great diversity of form. The vast majority can be attributed to strong gravitational tides generated in the close passage of two galaxies, to the extent that the terms 'peculiar galaxy' and 'interacting galaxy' are now virtually synonymous. These objects provided the first clear evidence that a galaxy's environment can profoundly affect its evolution (see GALAXY EVOLUTION).

Many peculiar galaxies are experiencing episodes of enhanced star formation, called starbursts. They also show a greater tendency to host ACTIVE GALACTIC NUCLEI (AGN) compared with the normal galaxy population. Conversely, when one examines the most luminous objects in the universe—quasars, radio galaxies and infrared galaxies—one often finds peculiar morphologies, suggesting a direct link between interactions and extreme levels of emission. Tidally induced mergers of separate galaxies almost certainly account for a substantial fraction of the local elliptical population. This process has probably played a key role in GALAXY FORMATION.

Peculiar galaxies can be used to deduce the structure of normal galaxies and in a few cases probe large-scale mass distributions. Observational and numerical studies of these objects offer important insights into phenomena that have shaped the formation and evolution of galaxies.

Galaxies that will not fit

EDWIN HUBBLE introduced his 'tuning fork' classification scheme in 1929, in which galaxies were grouped into spiral, elliptical and irregular families based on their appearance in photographic plates. However, even at this early stage a small number of galaxies defied these broad categories. Deep exposures of NGC 4038/39 (aka 'the Antennae') and NGC 5216/18 revealed long and faint filaments of light (see figure 1). Equally perplexing was the elliptical galaxy Messier 87 (M87, figure 1), which showed a remarkable blue linear 'jet' emanating from its core. As intriguing as these objects were, they seemed to be rare exceptions and attracted little attention. Their apparent scarcity was due to difficulties in recording extended and low-surface-brightness emission with the telescopes and photographic plates then in use. This situation changed dramatically with the advent of wide-field Schmidt cameras. On completion of the National Geographic–Palomar Sky Survey in 1956, the number of peculiar galaxies grew from a mere handful to many thousands—roughly 10% of the galaxies visible in the Sky Survey plates. This new population displayed a bewildering array of morphologies: luminous bridges and tails, often extending many galaxy diameters, ellipticals with faint ripples or dust lanes, ring-shaped galaxies, even systems that appeared to be dissolving. Figure 1 shows several examples taken from the Digitized Sky Survey and gives some idea of their varied (and beautiful) forms. Many of these were included in the photographic atlases of peculiar galaxies by Vorontsov–Vel'yaminov (1956) and Arp (1963), which are still widely used reference works.

To the early investigators, these striking objects suggested gigantic explosions, galaxies in birth, galaxies in fragmentation, material ejections from nuclei, galaxies compelled by strong magnetic forces—or entirely new forces, even the creation of matter. However, the earliest explanation has proven to be the most successful, namely *peculiar galaxies are the result of strong gravitational tides generated by near collisions of ordinary galaxies.* This was originally suggested by the fact that peculiar galaxies are usually found in close pairs, and often with symmetrically placed features. This collisional interpretation had been rejected initially because galaxy encounters were thought to be exceedingly rare and because tides were considered incapable of creating long and narrow plumes like those seen in 'the Antennae'. However, it was eventually realized that galaxies exist in groups, sometimes separated by only a few disk diameters. Galaxies should therefore experience several close passages over their lifetimes (see GALAXIES: INTERACTIONS AND MERGERS). It was Alar and Juri Toomre's landmark 1972 paper that conclusively showed how gravitational tides could produce systems like the 'the Antennae' through a near collision of two spirals. A wide range of peculiar morphologies could in fact result depending on the relative masses, inclinations, orbital speed and collision geometry of the two galaxies. Gravitational tides vary with distance like R^{-3}, so they are most significant over a brief interval near closest approach. It is here that large-scale peculiarities such as plumes and bridges are abruptly 'launched' into their trajectories. The Toomres also extended the work of Holmberg by suggesting that sufficient orbital angular momentum could be lost in an encounter for two galaxies to coalesce, producing something resembling an elliptical galaxy. Simple statistical considerations implied that most ellipticals in the NGC catalog could have arisen this way. The idea that galaxies were isolated island universes had been dramatically overthrown.

Peculiar galaxies have been studied extensively over the past 30 yr, both observationally and theoretically. During this period the tidal interpretation has proven to be so successful that the terms 'peculiar galaxy' and 'interacting galaxy' are often used interchangeably.

Peculiar galaxy morphologies

There is a great diversity of form among peculiar galaxies, as even a quick examination of the Vorontsov–Vel'yaminov or Arp atlases will show. Even so, a number of clear categories can be recognized:

Interacting spirals with tails and/or bridges

'Antennae'-like systems result from close passages of similarly massive spirals. Bridges (e.g. NGC 2535/36) require lower-mass companions to prevent quick capture and are thus less common. Both may extend 100–200 kpc from the host galaxies. Bridges and plumes originate in the outer disks, and are therefore often blue in color and gas rich. Some contain dwarf-galaxy-sized condensations of stars and gas that appear to be gravitationally bound.

Interacting spiral–elliptical pairs
Because their internal motions are not dominated by rotation, interacting ellipticals produce diffuse sprays of stars rather than tails and bridges. In spiral–elliptical encounters, therefore, a single tail or bridge is seen, and the spiral typically displays the most visible damage (e.g. NGC 274/5).

Shell galaxies
Roughly 40% of ellipticals show faint interleaved shells or ripples in their outer regions (e.g. Arp 230). These may be the result of weak tidal interactions or the cannibalization of another galaxy. The peculiar elliptical Centaurus A, for example, has both shells and a dust lane, suggesting the consumption of a gas-rich spiral.

Galaxies with optical jets
Remarkably linear filaments are sometimes found near peculiar spirals. Most are tidal tails and bridges that only appear linear owing to edge-brightening and projection effects (e.g. NGC 4676). The much rarer optical synchrotron jets are manifestations of AGN. M87 and 3C 273 are the best known examples.

cD and 'dumb-bell' galaxies
The centers of rich galaxy clusters are often occupied by giant ellipticals called cD galaxies. These frequently possess multiple nuclei, most likely from the cannibalization of another cluster galaxy. An extreme form of this class are 'dumb-bell' galaxies, which are binary ellipticals embedded in a common stellar envelope (e.g. NGC 750). These are expected to coalesce after a few orbits (i.e. $\sim 5 \times 10^8$ yr).

Merger remnants
Both the Vorontsov–Vel'yaminov and Arp atlases include objects now believed to represent the late stages in the merger of two galaxies (e.g. Arp 220). At this point they are roughly elliptical in appearance, although their vestigial tidal tails, large gas masses and double nuclei—generally visible only at radio and infrared wavelengths—betray their true origin.

Polar-ring galaxies
Roughly 0.5% of known S0 galaxies possess rings orbiting a plane perpendicular to the disk. NGC 4650A (figure 2) is the prototype polar-ring galaxy. The rings are often rich in gas and young stars and are believed to represent material captured during an interaction that has settled in semistable polar orbits. Spiral–spiral mergers, in which one is transformed into an S0, have also been proposed as a formation mechanism.

Ring galaxies
Ring galaxies such as the Cartwheel (figure 2) are created by the passage of a companion through a spiral's disk near the nucleus. This interaction crowds the disk's orbits into a large ring ($D_{ring} \sim$ 10–35 kpc) that propagates outward at speeds of ∼50–100 km s^{-1}. Observations show that ∼90% of the spiral's gas supply is concentrated in the ring, along with essentially all star formation activity.

The expected lifetimes of these peculiarities vary greatly. The multiple nuclei of cD and dumb-bell galaxies evolve in a deep and rapidly changing gravitational potential, and so are believed to be very transient, perhaps needing less than $\sim 10^8$ yr to merge. Tidal tails, bridges and sprays experience a much shallower potential, and should persist much longer, perhaps several billion years.

Most spirals show slightly distorted arms or minor asymmetries in their disks. These can be attributed to weak interactions with companions. Many otherwise 'normal' galaxies show peculiar morphologies at low light levels. Particularly dramatic examples have been discovered by David Malin using special techniques (see DETECTORS: PHOTOGRAPHY) to explore emission as faint as 0.5% of the night-sky glow (see figure 3). These structures may represent long-lived remnants of ancient interactions. There is in fact a wide range of morphological oddities among the general galaxy population. What we have been calling peculiar galaxies throughout this article actually represent the extreme end of a continuum.

Star formation in peculiar galaxies

It had been long noted that peculiar galaxies tended to be very blue in color, and often with unusually luminous star-forming complexes. Analysis of the UV excess Byurakan Survey galaxies, for example, showed that 40% possessed double nuclei or obvious tidal features. By the 1970s sufficient observational data had accumulated to examine possible links between unusual morphologies and enhanced STAR FORMATION activity. The most influential of these early investigations was that of Larson and Tinsley (1978), who compared the optical UBV colors of a normal galaxy sample taken from the Hubble atlas with peculiar galaxies from the Arp atlas. Figure 4, taken from that paper, shows that the Arp atlas galaxies are on average significantly bluer than the normal galaxy sample (i.e. smaller U-B for a given B-V) with a much wider spread of values. This could be simply understood if the peculiar galaxy sample had recently experienced brief episodes ($\sim 10^7$–10^8 yr duration) of elevated star formation activity called a starburst. The large color dispersion primarily reflects differences in the starburst's age and strength, and/or dust obscuration. Research over the last two decades has established a clear connection between peculiar morphology and the occurrence of starburst activity. Theoretical studies show that tidal interactions can be very effective in triggering starbursts by driving strong spiral or ring density waves or by transporting gas to the inner nucleus. Observations show that star

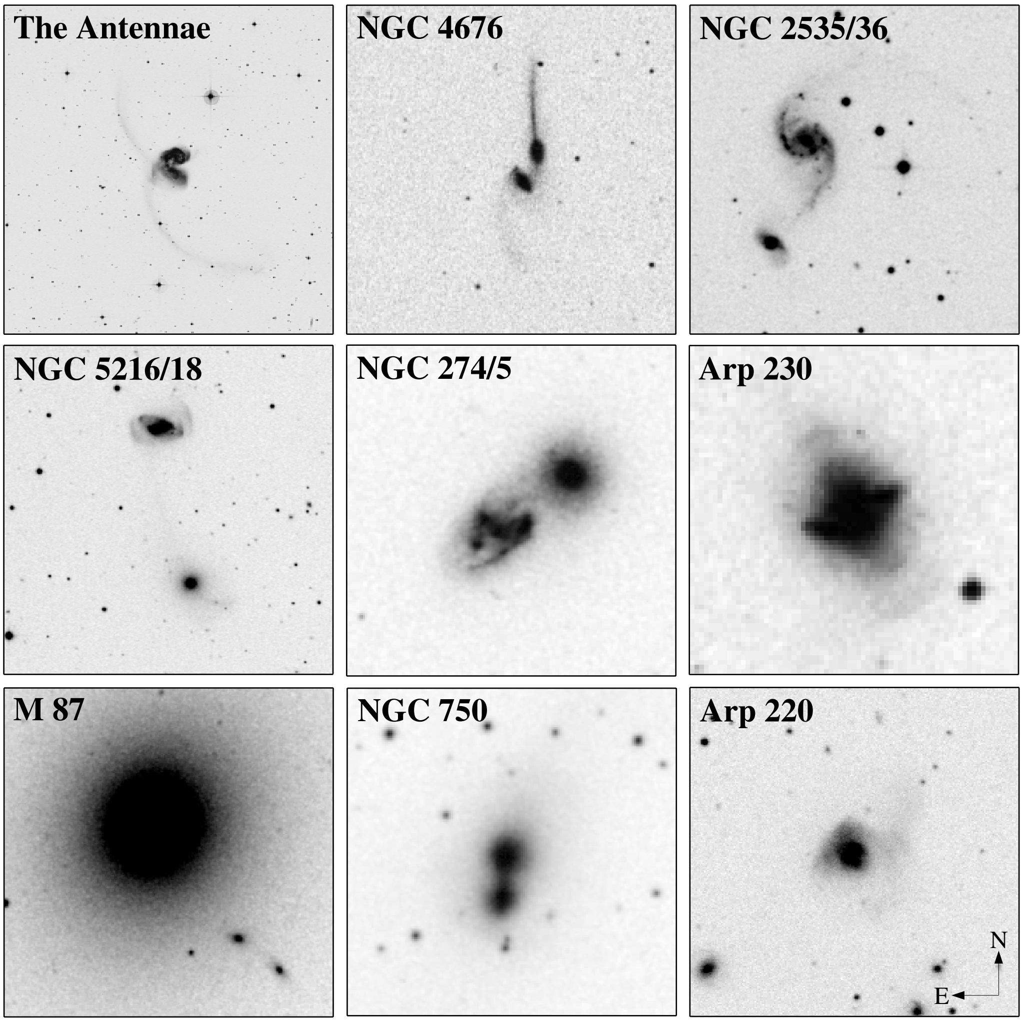

Figure 1. A montage of peculiar galaxies reproduced from the Digitized Sky Survey. They are presented in negative to make faint emission easier to see.

formation is increased only by modest factors of 2–3 over normal galaxies when averaged over the entire peculiar galaxy population. However, there is a wide range in star formation enhancement among individual peculiar galaxies, from essentially zero to several orders of magnitude. The induced star formation may be global in extent (e.g. the Cartwheel's ring). However, the most intense starbursts occur within the galaxy's inner kiloparsec. These nuclear starbursts tend to be found in the most strongly interacting systems. Excellent examples are the luminous infrared galaxies (LIRGs, e.g. Arp 220). LIRGs emit most of their total luminosity at infrared wavelengths ($\lambda > 5\ \mu$m), in at least half of the cases owing to dust heated by young massive stars. Astonishing star formation rates (SFR$\sim(10^2–10^3)M_\odot$ yr^{-1}) and gas masses ($M_{gas} \sim (10^{10}–10^{11})M_\odot$, i.e. a substantial fraction of the *total* gas mass) characterize their inner nuclear regions. LIRGs show a strong tendency to possess unusual optical morphologies. In the most luminous examples, essentially all are peculiar.

It should be emphasized that not all STARBURST GALAXIES appear highly peculiar. Also, not all peculiar galaxies are experiencing starbursts. This may reflect time delays between interaction and peak star formation, weak and quickly damped tidal perturbations, details of the collision or a lack of sufficient gas to fuel a starburst in the first place. Nevertheless, the frequency of starburst activity is much higher in peculiar galaxies. And, as the intensity of the starburst increases, so does the likelihood that the galaxy will possess a highly disturbed optical morphology.

Peculiar galaxies and active galactic nuclei

The first securely identified optical counterparts of powerful extragalactic radio sources (Cygnus A and Centaurus A) were strikingly peculiar. This fact suggested a direct connection between galaxy collisions and radio emission. However, subsequent observations found luminous radio emission to be far more likely to be

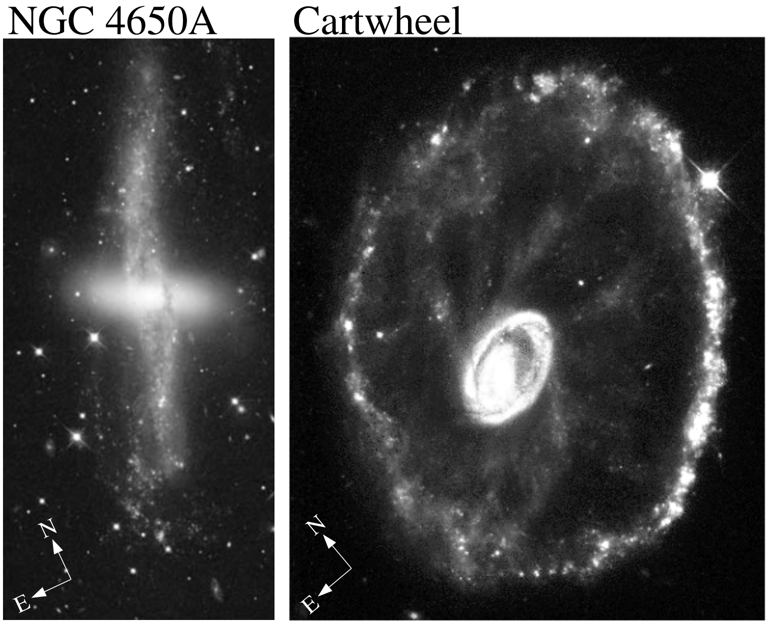

Figure 2. Two examples of peculiar rings: NGC 4650A (polar-ring galaxy) and the Cartwheel (ring galaxy). Both images were taken with the Hubble Space Telescope.

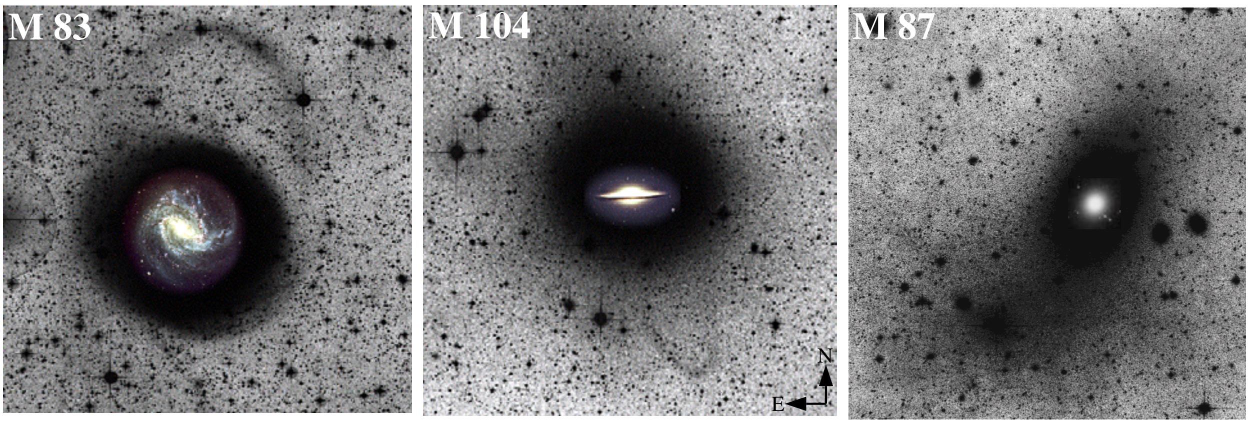

Figure 3. Enhanced photographs of nearby 'normal' galaxies by David Malin. The spiral galaxies M83 and M104 both show faint loops of starlight, while the elliptical galaxy M87 is embedded in an asymmetric spray of stars. More typical exposures have been inserted into the over-exposed centers to give an idea of their relative scales.

associated with the nuclei of rather ordinary looking ellipticals. The issue was reopened in the 1970s with the discovery that nuclear starbursts were common in peculiar galaxies. Theoretical results also suggested that interactions could efficiently transport gas to small radii and fuel an AGN's central engine. Recent surveys show that while the majority of galaxies with AGN in the local universe do not appear obviously peculiar, there is an increased tendency for peculiar galaxies to possess active nuclei. For example, Seyfert nuclei—the most common local type of AGN—occur more frequently in peculiar spirals than in normal spirals. The significance of this association increases with the degree of the morphological distortion. Further, one-third to one-half of the most powerful LIRGs appear to harbor heavily obscured AGN. These objects are invariably peculiar at optical wavelengths. In addition, ground-based imaging of low-redshift QUASARS shows that a significant fraction possess large-scale distortions, multiple nuclei or at least an excess of nearby peculiar companions. HST observations confirm that many quasars are morphologically peculiar. For example, of the 20 $z < 0.3$ quasars studied by Bahcall and collaborators (figure 5), more than a third are clearly interacting tidally, with half of the remainder showing faint extended structures resembling those of local merger remnants.

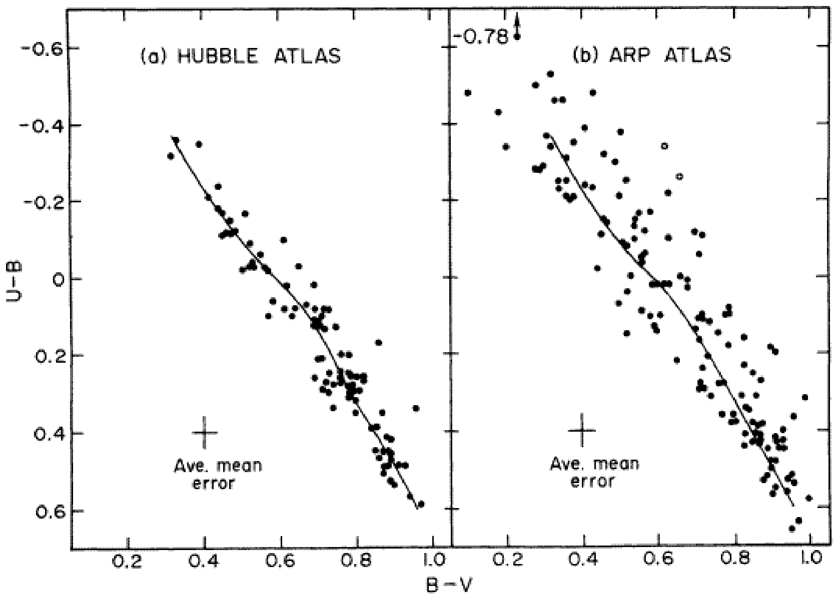

Figure 4. The UBV two-color distributions of normal (Hubble atlas) and peculiar (Arp atlas) galaxies reproduced from Larson and Tinsley (1978). The solid curve represents the mean through the Hubble atlas sample. Typical uncertainties in the colors are shown in each panel.

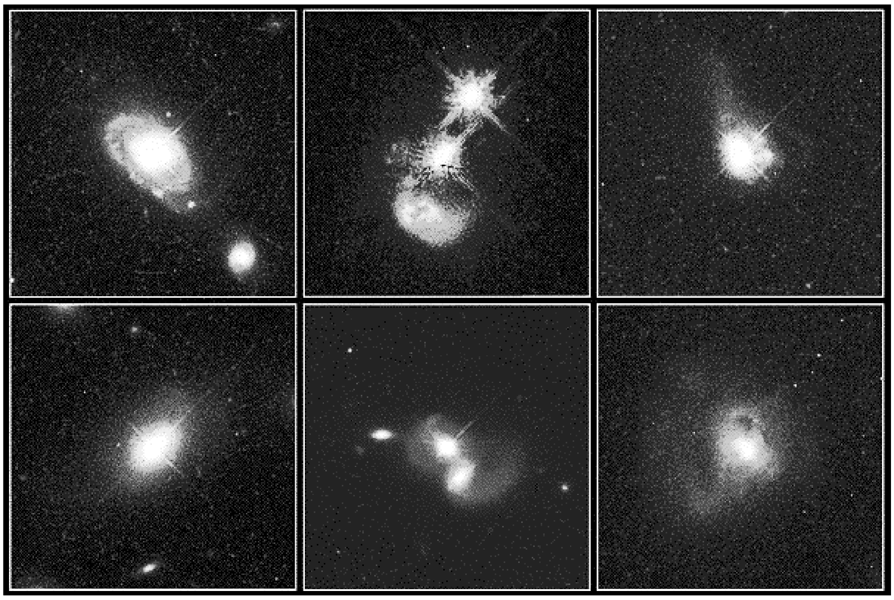

Figure 5. Optical images of low-redshift ($z < 0.3$) quasars taken with HST (Bahcall and collaborators, 1997). Note the close companions and/or obvious tidal features.

Again, most galaxies with AGN are not noticeably peculiar, and most peculiar galaxies do not possess AGN. Nevertheless, there is at least indirect evidence for a connection between galaxy interactions and at least some forms of powerful AGN.

Concluding remarks

The vast majority of peculiar galaxies represent highly perturbed ordinary galaxies. Observational and numerical studies of these systems can therefore provide insights into galactic structure. The kinematics of polar rings and tidal tails, for example, can be used to probe dark halos on scales much larger than ordinary optical or gas disks. Detailed computer simulations of interacting systems not only help refine the input galaxy models, they also allow one to better understand how galaxies might evolve in more complex environments such as compact groups or rich clusters. Further, several lines of evidence suggest that galaxies are assembled through the coalescense of dwarf galaxy sized components at high redshift, and there is evidence that at least some nearby ellipticals have arisen through mergers. The ongoing mergers and merger remnants in the peculiar galaxy population can thus serve as templates for the study of galaxy formation and evolution. Finally, the energy released by starbursts and AGN can have a major impact on the energy balance in a galaxy's interstellar medium. Likewise, studies of peculiar galaxies such as Arp 220 show that starbursts can also supply substantial amounts of heavy elements. Both processes appear to have been much more common at higher redshifts. These few examples show that peculiar galaxies are important for what they can tell us about the structure and evolution of galaxies and for providing local examples of processes that have shaped the chemical and luminosity evolution of the universe.

Bibliography

The peculiar galaxy literature is vast. Fortunately, there are a number of excellent reviews with extensive references, e.g.

Kennicutt R, Schweizer F and Barnes J 1996 *Galaxies: Interactions and Induced Star Formation (Saas-Fee Advanced Course 26, Lecture Notes 1996)* (Swiss Society for Astrophysics and Astronomy)

One would also benefit by reading such classic papers as

Holmberg E 1941 *Astrophys. J.* **94** 385
Larson R and Tinsley B 1978 *Astrophys. J.* **219** 46

and of course

Toomre A and Toomre J 1972 *Astrophys. J.* **178** 623

Perhaps the best introduction to this subject is simply to browse through the Vorontsov–Vel'yaminov and Arp atlases. Electronic versions exist on the web (both atlases can be found at nedwww.ipac.caltech.edu/level5/pi-galaxies.html), although the quality of Arp's atlas is such that one should try to locate a large format copy in a university science library.

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